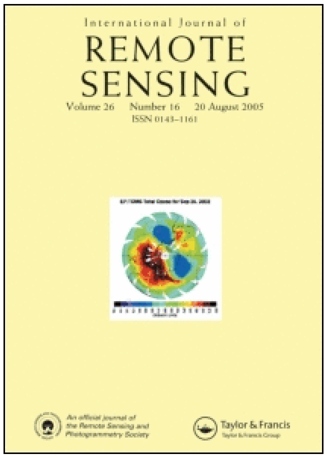

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Sea surface temperature GOES-8 estimation approach for the Brazilian coast

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Abstract. This work presents a quite consistent procedure for estimation of sea surface temperature (SST) using data from the new generation of the Geostationary Operational Environmental Satellite (GOES). The SST methodology is based on the classical split-window equation. The regional split-window coefficients (A_0, A_1, A_2 and A_3) are estimated by an algorithm regression taking as dependent variable three datasets, i.e. the SST derived from National Oceanic and Atmospheric Administration (NOAA)-14 polar-orbiting satellite and from buoys of Pilot Research Moored Array in Tropical Atlantic (PIRATA) and National Programme of Buoys (PNBOIA). This work shows that the main advantage of the GOES-8 SST algorithm, in comparison with the multi-channel sea surface temperature (MCSST) procedure using Advanced Very High Resolution Radiometer (AVHRR) data, is the high frequency sampling imagery (each half-hour) which permits a daily image with much less quantity of cloud contamination. The algorithm results using AVHRR/NOAA-14 as input dataset for the regression show that the accuracy of the GOES-8 SST algorithm is better than 1.0°C for all Brazilian coast. For regional estimation, the accuracy has been improved to around 0.5°C. Also, the accuracy of GOES-8 SST is better than 0.7°C using *in situ* SST collected from moored and drifting buoys.

1. Introduction

Sea surface temperature (SST) and surface wind play an important role for modelling the heating flux and in understanding of the interactions between the Earth's atmosphere and ocean. The current numerical weather and climate models require, as input, values of these parameters with high precision in order to achieve better results in terms of weather and climate forecasts. The accuracy of the SST, which is focused on this work, has been stipulated by the international tropical ocean global atmospheric (TOGA) programme to be equal to 0.3°C for weather forecasting (Barton *et al*. 1989). It is well known that the problems of SST retrieval using remotely sensed data are mainly due to the effects of the atmospheric gases and more specifically to the absorption by the water vapour in the atmosphere. This problem has been investigated since the early 1970s by several different workers (for

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example, Prabhakara *et al*. 1974, McMillin 1975, Deschamps and Phulpin 1980, Chedin *et al*. 1982, Price 1983, 1984, Holyer 1984, Becker 1987, Sobrino *et al*. 1991, França and Cracknell 1994, França and Carvalho 2001, and others).

The estimation of SST derived from the National Oceanic and Atmospheric Administration (NOAA) Advanced Very High Resolution Radiometer (AVHHR) data has been done for more than two decades by Barton (1995) and more recently from the Along-Track Scanning Radiometer (ATSR) data by Harris and Saunders (1996). Both radiometers (AVHRR and ATSR) are flying in Sun-synchronous polar orbits about 850 km above the ground. The new generation of Geostationary Operational Environment Satellite (GOES) series was launched in 1994 starting with GOES-8. The improvements undergone by the new generation of GOES series are related to the spatial resolution and signal-to-noise ratios which permit more precisely to measure the upwelling radiation (Menzel and Purdon 1994), although there are disadvantages to working with GOES-8, since it has no in-flight calibration capability yet and has two or three times more noise than the AVHRR/NOAA data (Legeckis and Zhu 1997).

Maul *et al*. (1978) and Zandlo *et al*. (1982) have developed algorithms for estimating SST using geostationary satellites. However, due to the high noise level and poor spatial resolution (16 km) of the thermal channels of the GOES series (GOES-5/6/7) by that time those algorithms were not successfully implemented. Legeckis and Zhu (1997) and Wu *et al*. (1999) derived SST using GOES-8 and GOES-8/9, respectively. The GOES data, which can be retrieved at a certain location 48 times a day, have great advantage over NOAA satellite series AVHRR data, which can be retrieved only twice a day. The GOES allows more possibility of acquiring SST data over a certain location that permits estimation of SST of larger cloudiness areas. Wu *et al*. (1999) mentioned the difficulties to achieve high radiometric precision with high spatial and temporal resolution taking into account that the geostationary satellite is orbiting 36 000 km above the Earth's surface. Knowing aforementioned difficulties, this paper presents a simple algorithm for estimation of SST using data from GOES-8. The regression coefficients of the SST GOES-8 have been estimated by a regression algorithm, as described in §3, using two different datasets as dependent variable, i.e. one dataset composed of match ups of sea temperature measurements at 1 m depth from PIRATE and PNBOIA (moored and drifting) buoys and the other dataset from AVHRR SST data from NOAA-14. In particular, the buoys were concentrated in the equatorial and south/south-east region of the Brazilian coast, which does not cover all the region of interest, allowing only regional GOES-8 SST regression coefficient. Thus the AVHRR SST data were utilized in the regression as dependent variable to estimate GOES-8 SST regression coefficient covering all the region of interest.

Considering that the Earth's surface is normally covered by a large amount of cloud at any time (Paltridge and Platt 1976), for reliable results from retrieval of SST using remotely sensed data absolutely cloud-free pixels are required. Following França and Cracknell (1995) a simple cloud-masking algorithm was adjusted for GOES-8 data in our studied region. The cloud-masking algorithm is composed of a chain of decision-making of several techniques where all image pixels are individually examined in order to determine if it is a cloud-free or cloud-contaminated one. The GOES-8 SST algorithm is being tested for operational implementation by the Centro de Previsão do Tempo e Estudos Climáticos (CPTEC) at the Brazilian Research Space Institute (INPE) and daily SST image have been produced since December 1999.

This paper is organized as follows. Detailed description of the data processing is provided in §2. In §3, the methodology to estimate SST using GOES-8 data, including the cloud-masking algorithm, is described. The performance of the implemented algorithm is shown and discussed in §4. In §5 conclusion and suggestions are presented.

2. Data processing

For the evaluation of the effectiveness of the methodology described in §3, nearly 50 AVHRR/NOAA-14 and GOES-8 datasets, as shown in table 1, were processed and used. These two datasets were selected as dependent variables in the regression equation (1) aiming to represent a wide spectrum of atmosphere stage of cloud-free atmospheric conditions in order to estimate equation (1) coefficients.

The AVHRR 10-bits data have been converted to SST images by the operational SST procedure in use at CPTEC/INPE. The AVHRR/NOAA-14 SST image was mapped to an equidistant projection with spatial resolution of 1.5 km using nearest neighbour interpolation by in-house software. The GOES-8 full resolution data (10-bits word) channels 1 (at 0.52–0.72 μm), 4 (at 10.2–11.2 μm) and 5 (at 11.5–12.5 μm) were processed corresponding to the radiometric and geometric correction using the TeraScan system available at CPTEC/INPE. This system was also responsible for calculating the satellite zenith angle; channel 1 albedo and brightness temperature of channels T_2, T_4, T_5.

Table 1. Dataset of GOES-8 and NOAA-14 images for equatorial and south/south-east regions of Brazil.

Year	Julian day	GOES (h UTC)	AVHRR (h UTC)	Year	Julian day	GOES (h UTC)	AVHRR (h UTC)
1998	191	1710	1646	1999	018	1810	1808
—	192	1710	1632	—	116	1810	1758
—	193	1810	1800	—	117	1810	1747
—	194	1810	1749	—	118	1810	1747
—	195	1810	1738	—	119	1810	1736
—	196	1710	1729	—	120	1710	1725
—	197	1710	1718	—	121	1710	1714
—	269	1710	1722	—	122	1710	1703
—	270	1710	1712	—	125	1810	1809
—	271	1710	1701	—	126	1810	1757
—	272	1710	1650	—	127	1810	1746
—	273	1710	1639	—	128	1810	1735
—	274	1810	1807	—	144	1810	1756
—	275	1810	1745	—	152	1810	1807
—	276	1810	1734	—	164	1810	1733
—	277	1710	1723	—	166	1710	1711
—	278	1710	1723	—	171	1810	1754
—	330	1810	1748	—	177	1810	1827
—	331	1810	1737	—	179	1810	1805
—	332	1710	1726	—	180	1810	1753
—	333	1710	1715				
—	334	1710	1704				
—	356	1810	1800				
—	357	1810	1749				
—	358	1810	1738				
—	359	1710	1727				
—	360	1710	1716				

In order to obtain the spatial resolution AVHRR/NOAA-14 SST image compatible to GOES-8 image, the AVHRR/NOAA-14 SST image underwent a pixel spatial degradation by a factor of four, i.e. each new AVHRR/NOAA-14 pixel represents the average of 4 pixels $\times$ 4 pixels.

The GOES-8 and AVHRR/NOAA-14 SST images were navigated using polynomial regression and taken as control points between the images the correspondent geographical co-ordinates. In general, the image accuracy was about one pixel. On the other hand, aiming to establish a regional GOES-8 SST algorithm for the equatorial and south/south-east of the Brazilian coast, SST obtained *in situ* measurements from the PIRATE and PNBOIA projects, as dependent variable of equation (1). Briefly, the PIRATE project consists of a set of moored buoys displaced at specific co-ordinates along the equatorial Atlantic Ocean. Those buoys collect oceanographic *in situ* measurements of several physical quantities including daily averaged SST data, which were used in this work. Regarding the south/south-east of the Brazilian coast, there is a project called PNBOIA that is responsible for launching drifting buoys for collecting several physical oceanographic quantities including SST on a regular basis every year. In particular, the SST measurement is collected four times a day. To estimate regional equatorial, south/south-east and south/south-east/equatorial regression coefficients of equation (1) of the GOES-8 SST algorithm, as described in §3, 305 samples of moored buoys and 1366 samples of drifting buoys measurements of SST collected at approximately 1 m depth were used during the period from January 1999 to April 2000, respectively. Those SST buoys samples were selected taking into account the minimum difference between pixel geolocation (latitude and longitude) and buoys' position; besides, the pixel should satisfy the criteria of the GOES-8 cloud-masking algorithm for cloud free. Figure 1 shows the paths of the four drifting buoys from PNBOIA used in this work during the period July 1999 to April 2000.

3. Methodology

The purpose of this study is to present an experimental system of daytime and night-time composite SST estimation using GOES-8 data for Atlantic Ocean water on the Brazilian coast. Figure 2 shows the flowchart of the methodology that is composed of four main steps, i.e. pre-processing, which corresponds to the radiometric and geometric correction procedure mentioned in §2; cloud masking; atmospheric correction; and the daytime and night-time composite GOES-8 SST estimation. The last three steps are described in the following sections.

3.1. *Cloud detection*

França and Cracknell (1995) have presented studies of cloud detection using AVHRR/NOAA data covering north-eastern Brazil. Following their methodology in this work a cloud-masking procedure was adapted for daytime and night-time GOES-8 data using channels 1, 4 and 5 and 2, 4 and 5, respectively. The procedure is based on a chain of decision making that is composed of statistical thresholds techniques where all image pixels are individually examined in order to determine whether they are cloud-free or cloud contaminated. The thresholds have been determined for the cloud-masking techniques without any sort of atmospheric correction.

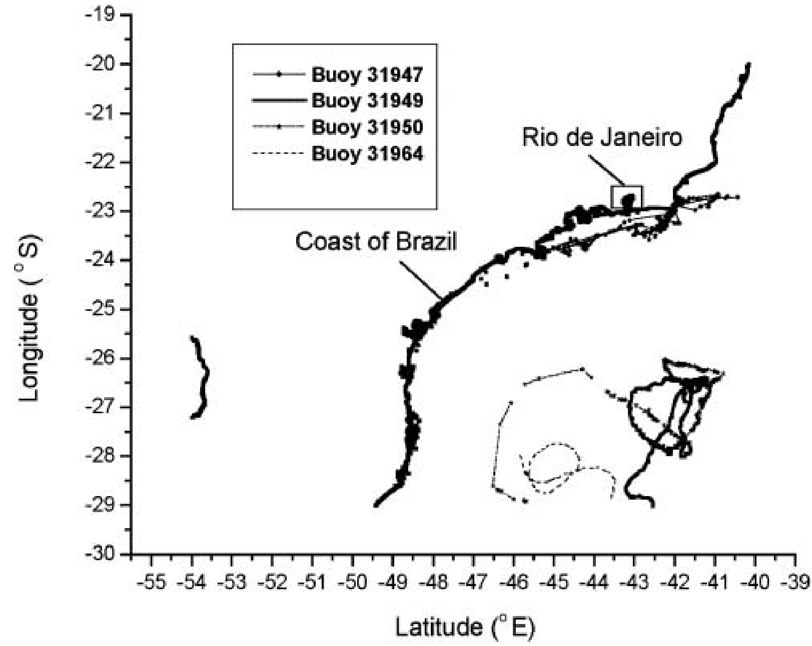

Figure 1. The paths of the four PNBOIA's project buoys in the south/south-east region of the Brazilian coast during the period July 1999 to April 2000.

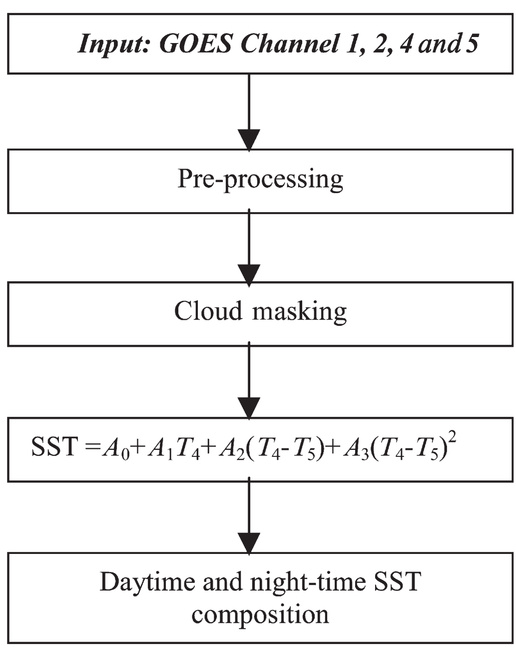

Figure 2. Flowchart of the GOES-8 SST algorithm.

3.2. *Atmospheric correction*

The accuracy of retrieving surface physical quantities, for example SST estimation, by remotely sensed data depends on the atmospheric corrections model that is used taking into account the variation of surface emissivity. In the case of SST retrieval, the surface emissivity problem is quite simple to solve because the emissivity of the sea surface is close to unit in the spectral region from 8 to 14 μm. The average emissivity of the ocean surface is normally assumed equal to 0.98. Due to the above assumption and the modern AVHHR that permitted development of the split-window technique, SST can be retrieved operationally from AVHHR/NOAA data (McClain *et al.* 1985, Walton *et al.* 1998). These algorithms for SST retrieval using thermal AVHRR/NOAA-14 data are based on regression of the *in situ* SST measurements (from ships, or buoys at approximately 1 m depth) versus thermal remotely sensed radiance. The atmospheric correction approach presented in this paper followed a suggestion by Wu *et al.* (1999). The exclusion of view angle dependence is quite similar to our situation in this work. Then, the atmospheric correction is done by the regression equation as follows

$$SST = A_0 + A_1\ T_4 + A_2(T_4 - T_5) + A_3(T_4 - T_5)^2 \tag{1}$$

where T_4 and T_5 represent brightness temperature of GOES-8 thermal channels 4 and 5, respectively. The SST is, as mentioned in §2, derived from the AVHRR/NOAA-14 SST or buoys SST *in situ* measurements. The difference value T_4–T_5 represents the variation of water vapour concentration present in a certain atmospheric column. The atmospheric absorption in a wet atmospheric state shows a quadratic behaviour versus water vapour for the difference T_4–T_5 as shown by Ho *et al.* (1986) and França and Cracknell (1994). The estimation results of the coefficients A_0, A_1, A_2 and A_3 of equation (1) are shown in detail in §4 using the above-mentioned data.

3.3. *Daytime and night-time SST compositions*

The daily GOES-8 SST image generation is based on 48 GOES-8 image sets for a given day where the daytime and night-time SST composite are calculated using channels 1, 4 and 5 and channels 2, 4 and 5, respectively. The daytime and night-time SST compositions are realized using the highest SST for each pixel considering all GOES-8 images from diurnal and nocturnal periods, respectively.

4. Results and discussion

The results of the SST estimative, using equation (1), were obtained with extensive range of atmospheric conditions for all seasons of the year in the study region. Table 2 presents all regression coefficients for equation (1) considering the two study regions, i.e. south/south-east and equatorial regions of the Brazilian coast. The linear least-square regression between GOES-8 and AVHRR SST data shows a medium standard deviation equal to 0.29 for the south/south-east region, where 19.941 free cloud pixels were collected from 1998 to 1999 (according to table 1). Although the adjusted coefficients do not show all possibilities of atmospheric conditions in the south/south-east region, these coefficients are quite reasonable when compared with the results of the AVHRR/NOAA-14 SST (considered terrestrial truth). Seasonal or daily adjustment for equation (1) was obtained using GOES-8 and AVHRR/NOAA-14 SST data with an accuracy of around 1.0°C or less (see table 1).

A comparison between the SST results obtained via AVHRR/NOAA-14 and GOES-8 for 229 coincident pixels is presented in figure 3. These results show an excellent coherence between GOES-8 and AVHRR/NOAA-14 SST results for all

Table 2. Summary of GOES-8 regression coefficients of equation (1) using AVHRR/NOAA-14 SST estimation and buoys SST measurements for the south/south-east, equatorial and both regions.

Region	A_0	A_1	A_2	A_3	Samples	Standard deviation (°C)
south/south-east Adjust: GOES-8 and AVHRR/NOAA-14 SST	4.2769	0.9243	−0.1799	0.0049	19.941	0.29
equatorial Adjust: GOES-8 and AVHRR/NOAA-14 SST	17.4158	0.5117	−1.3550	0.2379	12.712	0.26
south/south-east Adjust: GOES-8 and buoys	6.3684	0.7952	1.1181	0.0068	2512	0.55
equatorial Adjust: GOES-8 and buoys	17.4121	0.1700	3.4273	−0.4159	519	0.70
south/south-east and equatorial Adjust: GOES-8 and AVHRR/NOAA-14 SST	1.0153	1.1343	−1.0447	0.4400	49.591	1.01

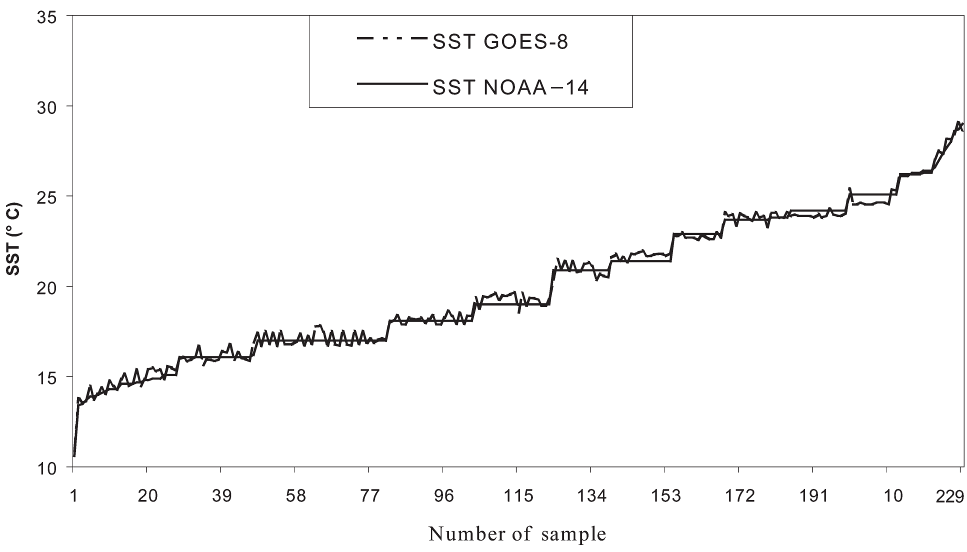

Figure 3. Comparison between coincident 229 pixels (samples) of AVHRR/NOAA-14 SST (solid line) and GOES-8 SST (dashed line) showing that the range temperature varies from approximately 10°C to 30°C.

situations. It is worthwhile to note that the results of AVHRR/NOAA-14 SST estimation were more stable than those of GOES-8 SST estimation with small fluctuations. Such fluctuations are due, mainly, to the fact that the GOES-8 data were two or three times noisier than the AVHRR/NOAA data (Legeckis and Zhu 1997). This difference is also related to a longer optical path of the GOES-8 data sensors than those of AVHRR/NOAA sensors.

Figure 4 shows the performance of equation (1) using the GOES-8 regression coefficients compared with data of the PNBOIA and PIRATE project buoys at a

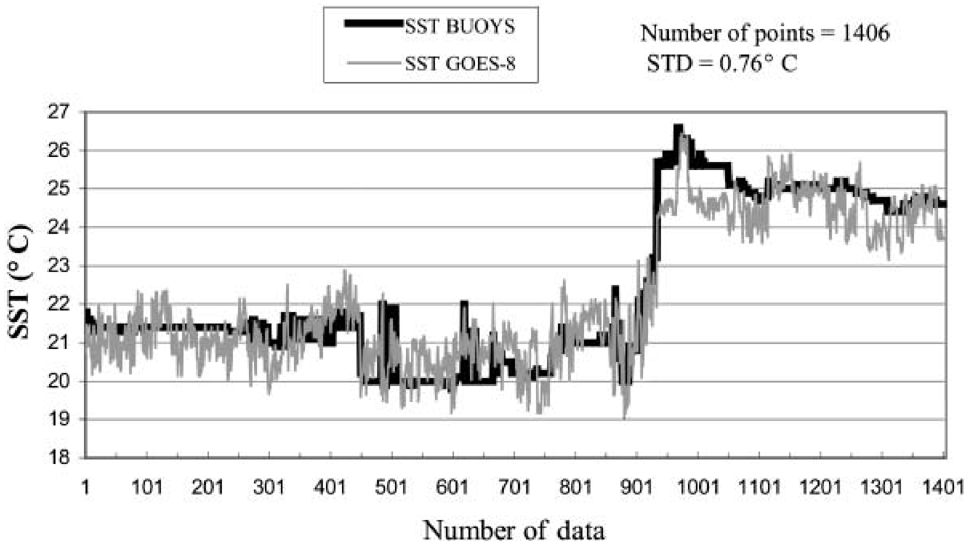

Figure 4. Comparison between GOES-8 SST and 1406 SST *in situ* measurements taken from PNBOIA and PIRATE buoys (drifting and moored) projects.

depth of 1 m in the south/south-east and equatorial regions. The GOES SST result fluctuations are mainly due to GOES-8 sensor noise and atmospheric effects.

Figure 5(*a*) and (*b*) shows an example of a sequence of daytime and night-time SSTs composite which represents the nocturnal and diurnal SST, respectively, for all the coast of Brazil from 6 to 8 October 2000. This figure is a sample result of a software program that has been developed, tested and implemented for SST at CPTEC/INPE. Although GOES-8 SST data obtained were noisier than those of AVHRR/NOAA-14 SST, cloud elimination was more effective as shown in figure 5(*a*) and (*b*) which represents an almost no cloud contaminated image for a composition of a three-day GOES-8 SST image. On the other hand, it needs at least two weeks of AVHRR/NOAA-14 SST images to obtain the same result in the study region.

One of the great capabilities of GOES-8 is the acquisition of a huge area of the Earth (North and South America continent water) at each half-hour. This allows monitoring of diurnal SST cycles. The study was done in Santa Catarina state on the Brazilian coast. Two fixed points (land and sea) were selected to retrieve the GOES-8 land surface temperature (LST) and SST, respectively. The procedure to extract surface temperature was done for three days from Julian days 274–276 of 1999. The same GOES-8 SST algorithm estimated the LST; the idea was only to evaluate qualitatively the diurnal LST variation. The diurnal temperature cycle on land was very evident because of the large changes in the diurnal surface temperature. The ocean temperature changes are relatively small (Legeckis and Zhu 1997). The values of surface temperature are normalized, from 0 to 1, to reveal the difference between land and ocean temperature on the Santa Catarina coast. The maximum value for land is 43.0°C and for sea 23.5°C; these values are equivalent to 1. Figure 6 shows the magnitude of diurnal ocean and land cycle temperature. The peaks of temporal LST and SST curve changes are quite different. The

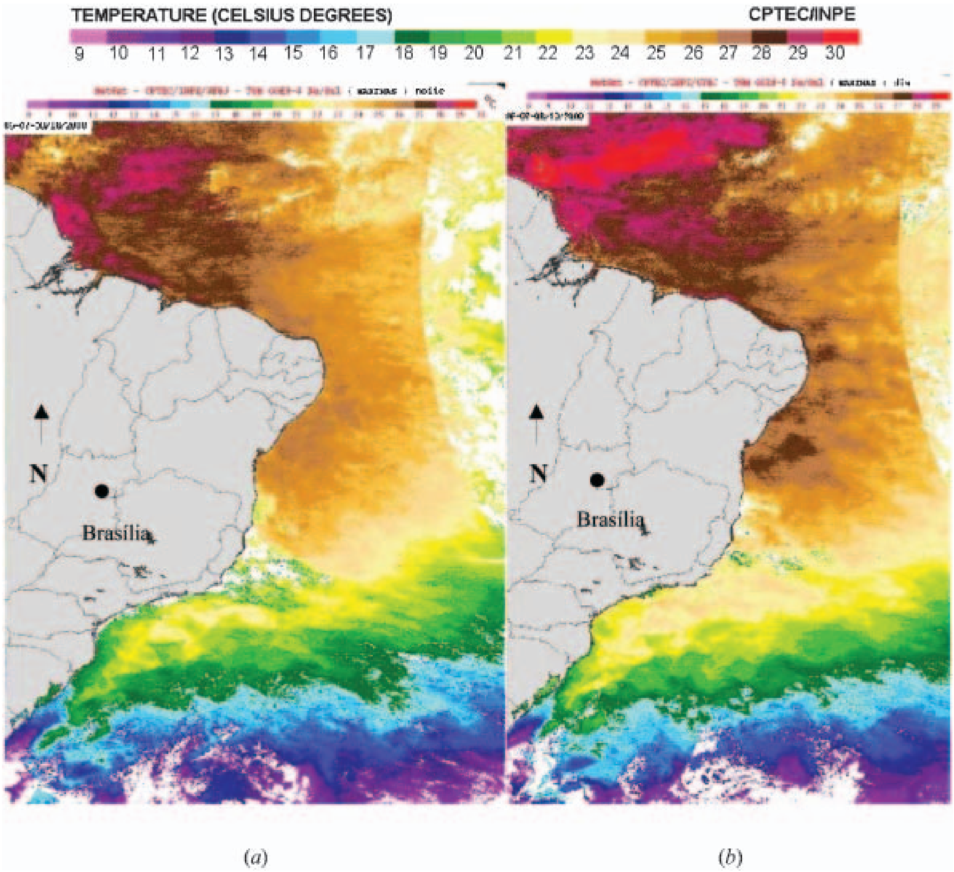

Figure 5. (*a*) Nocturnal and (*b*) diurnal GOES-8 SST composition during the period 6–8 October 2000.

temperature peak occurred on land and sea around 15:30 GMT and 17:00 GMT, respectively. The SST variation is about 2.0°C.

Table 2 also presents regression coefficients for equation (1) estimated by linear least-square regression between GOES-8 SST and *in situ* SST measurements using two groups of buoys as aforementioned. The regression standard deviations are 0.55°C and 0.7°C for south/south-east and equatorial regions, respectively. Figure 4 presents results comparison between GOES-8 and buoys SST for 1406 samples taken from both study regions, for which the STD is 0.76°C.

In order to achieve a better SST estimation via remotely sensed thermal data, atmospheric and optical path problems should be minimized and thus regional coefficients are required. As an example for the aforementioned we have used regression coefficients established by Maturi *et al*. (2000) for most of the Western Hemisphere (30°W–180°W, 45°N–60°S) using GOES data and its results underestimated the SST by about 5.0°C when applied and compared with 1 m depth SST from buoys used in the study area of this work.

5. Conclusions

It has been shown that GOES-8 estimated quite well the SST. It has confirmed that the GOES-8 SST can be retrieved with good accuracy by calibrating with

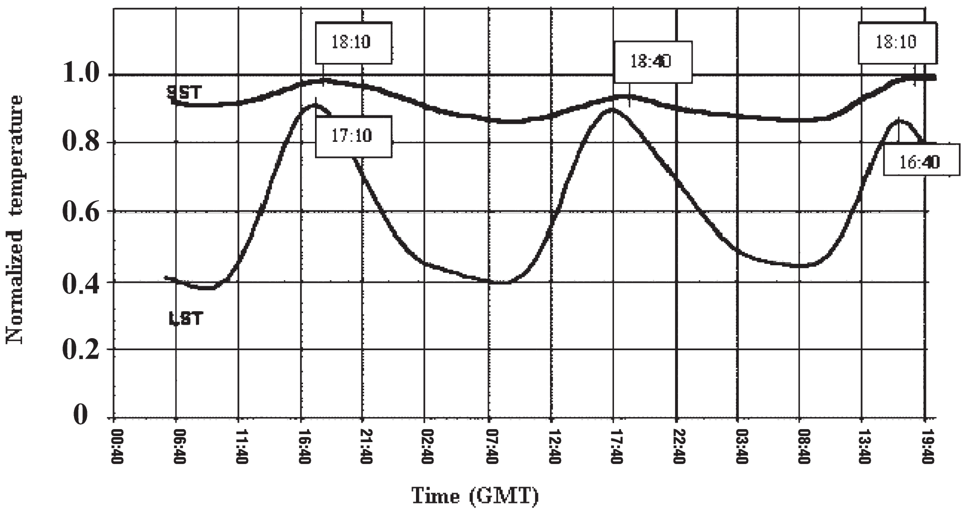

Figure 6. The normalized diurnal cycle temperature of two fixed points on land and sea of a time series of GOES-8 images in Santa Catarina State from Julian days 274 to 276 of 1999.

AVHRR SST as proposed by Legeckis and Zhu (1997). The GOES-8 SST has two great advantages: first, it has a greater area coverage; and, secondly, it has higher temporal frequency with more effective cloud elimination. These two advantages are very important for large-scale SST monitoring such as the Brazilian coastline. It is important to note that GOES-8 SST algorithm coefficients were estimated taking the spectrum range of AVHRR SST from approximately 10–30°C (figure 3) and the GOES-8 zenith angle ranging from 30–65°. Thus, the parameters obtained in this work did not show all possible atmospheric and oceanic conditions. A specific set of parameters is required to obtain a SST estimation model for a specific region as mentioned. An accuracy of around 1°C was obtained from the GOES-8 data, which is quite acceptable. Nevertheless, it is suggested that a suitable adjustment of cloud masking according to regional and seasonal variations of atmospheric conditions is needed to improve further the estimation accuracy.

Improvements in cloud masking and a better study on atmospheric conditions are necessary to achieve a better quality of SST. In addition, the reduction of noise and a better resolution of GOES IR sensor are necessary to have good identification of cloud-free ocean, which would permit an easier study of ocean phenomena.

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References

BARTON, I. J., 1995, Satellite-derived sea surface temperature: currents status. *Journal of Geophysical Research*, **100**, 8777–8790.

BARTON, I. J., ZAVODY, A. M., O'BRIEN, D. M., CUTTEN, D. R., SAUNDERS, R. W., and LEWELLYN-JONES, D. T., 1989, Theoretical algorithms for satellite-derived sea surface temperature. *Journal of Geophysical Research*, **94**, 3365–3375.

BECKER, F., 1987, The impact of spectral emissivity on the measurement of land surface temperature from a satellite. *International Journal of Remote Sensing*, **8**, 1509–1522.

CHEDIN, A. N., SCOTT, A., and BERROIR, A., 1982, A single channel, double viewing angle method for sea surface temperature determination from coincident Meteosat and TIROS-N radiometric measurements. *Journal of Applied Meteorology*, **21**, 613–618.

DECHAMPS, P. Y., and PHULPHIN, T., 1980, Atmospheric correction of infrared measurements of sea surface temperature using channels at 3.7, 11 and 12 μm. *Boundary-Layer Meteorology*, **18**, 131–143.

FRANÇA, G. B., and CARVALHO, W. S., 2001, Estimativa da temperatura da superfície do mar na costa brasileira utilizando dados GOES-8. Revista Pesquisa Naval, special edition of Revista de Pesquisa Marítima, Editora Vozes, vol. 14, pp. 311–319.

FRANÇA, G. B., and CRACKNELL, A. P., 1994, Retrieval of land and sea surface temperature using NOAA-11 AVHRR data in north-eastern Brazil. *International Journal of Remote Sensing*, **8**, 1695–1712.

FRANÇA, G. B., and CRACKNELL, A. P., 1995, A simple cloud masking approach using NOAA AVHRR-daytime data for tropical areas. *International Journal of Remote Sensing*, **9**, 1697–1705.

HARRIS, A. R., and SAUNDERS, M. A., 1996, Global validation of the Along-Track Scanning Radiometer against drifting buoys. *Journal of Geophysical Research*, **101**, 12 127–12 140.

HO, D., ASEM, A., and DESCHAMPS, P. Y., 1986, Atmospheric correction for the sea surface temperature using NOAA-7 AVHHR and METEOSAT-2 infrared data. *International Journal of Remote Sensing*, **7**, 1323–1333.

HOLYER, R. J., 1984, A two-satellite method for measurement of sea surface temperature. *International Journal Remote Sensing*, **5**, 115–131.

LEGECKIS, R., and ZHU, T., 1997, Sea surface temperatures from GOES-8 geostationary satellite. *Bulletin of the American Meteorological Society*, **78**, 1971–1983.

MATURI, E., LI, X., and WU, X., 2000, GOES sea surface temperature products in NOAA/NESDIS. Conference preprint by the American Meteorological Society of the 10th Conference on Satellite Meteorology and Oceanography, 9–14 January 2000, Boston, MA, USA.

MAUL, J. A., WEBB, P., YANAWAY, A., and BAIG, S. R., 1978, Geostationary satellite observations of Gulf Stream meanders: infrared measurements and time series analysis. *Journal of Geophysical Research*, **83**, 6123–6131.

MCCLAIN, E. P., PICHEL, W. G., and WALTON, C. C., 1985, Comparative performance of AVHRR-based multi-channel sea surface temperature. *Journal of Geophysical Research*, **90**, 11 587–11 601.

MCMILLIN, L. M., 1975, Estimation of sea surface temperatures from two infrared window measurements with different absorption. *Journal of Geophysical Research*, **80**, 5113–5117.

MENZEL, W. P., and PURDON, J. F. W., 1994, Introducing GOES-I: the first of a new generation of Geostationary Operational Environmental Satellites. *Bulletin of the American Meteorological Society*, **75**, 757–780.

PALTRIDGE, G. W., and PLATT, C. M. R., 1976, *Radiative Processes in Meteorology and Climatology* (New York: Elsevier).

PRABHAKARA, C., DALU, G., and KUNDE, V. G., 1974, Estimation of surface temperature from remote sensing in the 11 to 13 μm window region. *Journal of Geophysical Research*, **79**, 5039–5045.

PRICE, J. C., 1983, Estimating surface temperature from satellite thermal infrared—a simple formulation for the atmospheric effect. *Remote Sensing of Environment*, **13**, 7231–7237.

PRICE, J. C., 1984, Land surface temperature measurements from the split window channels of the NOAA 7 Advanced Very High Resolution Radiometer. *Journal of Geophysical Research*, **89**, 7231–7237.

SOBRINO, J. A., COLL, C., and CASELLES, V., 1991, Atmospheric correction for land surface-temperature using NOAA-11 AVHRR channel-4 and channel-5. *Remote Sensing of Environment*, **38**, 19–34.

WALTON, C. C., PICHEL, W. G., SAPPER, J. F., and MAY, D. A., 1998, The development and operational application of non-linear algorithms for the measurements of sea surface temperature with NOAA Polar-orbiting Environmental Satellite. *Journal of Geophysical Research*, **103**, 27 999–28 012.

WU, X., MENZEL, W. P., and WADE, G. S., 1999, Estimation of sea surface temperatures using GOES 8/9 radiance measurements. *Bulletin of the American Meteorological Society*, **80**, 1127–1138.

ZANDLO, J. A., SMITH, W. L., MENZEL, W. P., and HAYDEN, C. M., 1982, Surface temperature determination from amalgamation of GOES and TIROS-N measurements. *Journal of Applied Meteorology*, **21**, 44–50.